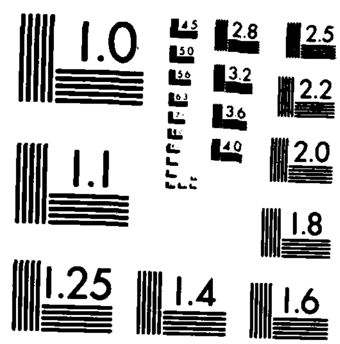
AD-A188 190 THEORETICAL AND OBSERVATIONAL PROBLEMS WITH 'HOLES' IN THE FAR UV DAYGLOW(U) NAVAL RESEARCH LAB WASHINGTON DC R R MEIER ET AL. 05 NOV 87 NRL-9078 1/1

UNCLASSIFIED F/G 4/1 NL



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Naval Research Laboratory
Washington, DC 20375-5000

NRL Report 9078

Theoretical and Observational Problems with "Holes" in the Far UV Dayglow

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November 5, 1987

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b RESTRICTIVE MARKINGS: AD-A188 190

2a SECURITY CLASSIFICATION AUTHORITY

2b DECLASSIFICATION / DOWNGRADING SCHEDULE

3 DISTRIBUTION / AVAILABILITY OF REPORT

4 PERFORMING ORGANIZATION REPORT NUMBER(S): NRL Report 9078

5 MONITORING ORGANIZATION REPORT NUMBER(S)

6a NAME OF PERFORMING ORGANIZATION: Naval Research Laboratory

6b OFFICE SYMBOL (If applicable): Code 4140

7a NAME OF MONITORING ORGANIZATION

6c ADDRESS (City, State, and ZIP Code): Washington, DC 20375-5000

7b ADDRESS (City, State, and ZIP Code)

8a NAME OF FUNDING / SPONSORING ORGANIZATION: Office of Naval Research

8b OFFICE SYMBOL (If applicable): ONR

9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c ADDRESS (City, State, and ZIP Code): Arlington, VA 20362-5000

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO
61153N		RR033-02-4A	DN155-012

11 TITLE (Include Security Classification): Theoretical and Observational Problems with "Holes" in the Far UV Dayglow

12 PERSONAL AUTHOR(S): Meier, R. R. and Chubb, T. A.

13a TYPE OF REPORT: Final

13b TIME COVERED: FROM ________ TO ______

14 DATE OF REPORT (Year, Month, Day): 1987 November 5

15 PAGE COUNT: 11

16 SUPPLEMENTARY NOTATION

17 COSATI CODES

FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number):
Radiative transfer model
Dayglow observations ;
Atmospheric phenomena

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Results of an OI 1304 Å radiative transfer model indicate that it is highly unlikely that "holes" in the Dynamics Explorer-1 (DE-1) dayglow observations are caused by either absorptive material imbedded in the atmosphere or to a depletion of atomic oxygen in an atmospheric column. An alternative explanation of absorbing clouds between the spacecraft and the emitting atmosphere is not precluded by the theory. In addition, observations from a far UV experiment on Orbiting Geophysical Observatory-4 (OGO-4) are examined for events comparable to the DE-1 holes. Some 200 events would be expected from the OGO-4 N_2 Lyman-Birge Hopfield (LBH) band data if the holes are atmospheric phenomena lasting on the order of minutes. Alternatively, if the holes are the result of passage of absorbing clouds across detector fields of view, 30 events would have been expected in OGO-4 data; however, their short occurrence time would make them difficult to detect, on the average. No evidence of holes was found in the OGO-4 data.

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21 ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a NAME OF RESPONSIBLE INDIVIDUAL: R. R. Meier

22b TELEPHONE (Include Area Code): (202) 767-2773

22c OFFICE SYMBOL: Code 4140

CONTENTS

THEORETICAL AND OBSERVATIONAL PROBLEMS WITH "HOLES" IN THE FAR UV DAYGLOW

INTRODUCTION

In a recent paper, Frank et al. (1986a) report the observation from the Dynamics Explorer-1 (DE-1) spacecraft of severe depletions in the far ultraviolet (FUV) dayglow. The decrease in brightness is as much as 80% to 95% of nearby emission levels. In the images constructed from the scanning photometer data, the depletions have a holelike appearance. The phenomena were observed primarily in the OI 1304 Å channel, although the authors report that holes can also be identified in the weaker N_2 Lyman-Birge Hopfield (LBH) molecular bands in the dayglow and above the Earth limb in H Lyman alpha. The characteristics of the holes are that they occupy an area of typically 2000 km^2, evolve over a period of several minutes, and occur over the dayside upper atmosphere with a frequency of about 10 holes/min or a globally averaged rate of 6.1×10^{-16} $m^{-2}s^{-1}$

Frank et al. (1986b) interpret these observations as the influx of "small" (100-ton) cometlike objects, which deposit 4×10^{30} molecules of H_2O in the upper atmosphere per event. Frank et al. (1986b) postulate that this "piston" of cometary material could compress the atmosphere, causing a depletion of atmospheric gas in a column, producing a *hole;* in addition, the cometary gas could cause absorption of FUV radiation from below. They argue that based on the work of Meier and Lee (1982) (discussed later in this report), the altitude range of the absorbing clouds should be above 250 to 350 km. They also calculate that the diffusive recovery time for a 25-km-diameter hole void of atomic oxygen in this attitude range is of the order of 1 min, in agreement with the lifetime of an FUV hole observed from DE-1.

This report presents theoretical arguments that show the unlikelihood that holes of the postulated composition within the atmosphere would be observable by the DE-1 instrument. Data obtained from the Naval Research Laboratory (NRL) FUV photometric instrument on the Orbiting Geophysical Observatory-4 (OGO-4) are examined for an indication of "holes" in the airglow. In the Discussion and Conclusions Section of this report, the implications of the theoretical and experimental OGO-4 results are used to put constraints on an alternative explanation of the DE-1 observations: that FUV absorption is occurring above the atmosphere.

THEORETICAL CONSIDERATIONS OF OI 1304 Å MULTIPLE SCATTERING

In the scenario given by Frank et al. (1986b) a "piston" of cometlike gas compresses the atmosphere resulting in a void of atmospheric oxygen atoms in its trail and (presumably) absorption of FUV photons from below. In this section of the report, we use a radiative transfer model to calculate the contribution function, or distribution of radiation reaching the top of the atmosphere from each altitude increment. This is used to show that a substantial contribution of the radiation originates at high altitudes, and therefore this *foreground emission* prevents depletion of the airglow by as much as 80% to 95%, unless the trail left behind an entering comet were devoid of emitters and aligned close to the line of sight of an observing instrument. Of course depletions caused by absorptive material above the atmosphere cannot be precluded by the theory.

Manuscript approved June 24, 1987.

Meier and Lee (1982) have developed a Monte Carlo model that simulates the transport of 1304 Å radiation in optically thick planetary thermospheres. The model has been applied successfully to satellite and rocket observations of the aurora and airglow of Earth and the airglow of Venus. The multiple scattering properties of the 1304 Å triplet within atomic oxygen atmospheres are well understood. Contrary to the statement by Frank et al. (1986b), the Meier and Lee paper does not contain sufficient information to place limits on the altitude of an absorbing cloud. Since the intensities are from an optically thick (10^5 at line center) atmosphere, information about the altitude of origin of observed photons cannot be obtained from altitude profiles of the integrated intensity.

We modified the Monte Carlo model of Meier and Lee to determine the altitude or origin of photons leaving the top of atmosphere. Figure 1 shows the contributions to the intensity as viewed vertically downward from outside the atmosphere, from scattering within each altitude interval. Both photoelectron and solar resonant scattering excitation sources are shown. Specifically, the frequency-dependent vertical intensity crossing each altitude grid, caused by multiple scattering in the altitude increment between that altitude grid and the one just below, is accumulated in the model. Each of these intensities is then multiplied by the frequency-dependent probability of reaching the top of the atmosphere and then integrated over frequency. Thus the points in Fig. 1 represent the incremental contribution (in Rayleighs) to the intensity leaving the top of the atmosphere from each altitude interval; simple summing of all points gives the total intensity leaving the top of the atmosphere. The results of this exercise showed that when viewing the atmosphere vertically downward from above and with the sun at 56° from zenith (the model atmosphere of Meier and Lee), about 4.6 kR is due to photoelectron excitation and 3.1 kR is due to resonant scattering of sunlight. For the photoelectron source, 35% of the photons leaving the atmosphere vertically have their last scattering above 300 km, 36% have their last scattering between 200 and 300 km, and 29% between 100 and 200 km. The results for solar scattering are 38% exiting from above 300 km, 12% from 200 to 300 km, and 50% from 100 to 200 km. Thus 35% to 38% of the observed emission comes from above 300 km. This is the result of the fact that oxygen atoms above that altitude are illuminated directly by the sun and indirectly by multiply scattered radiation.

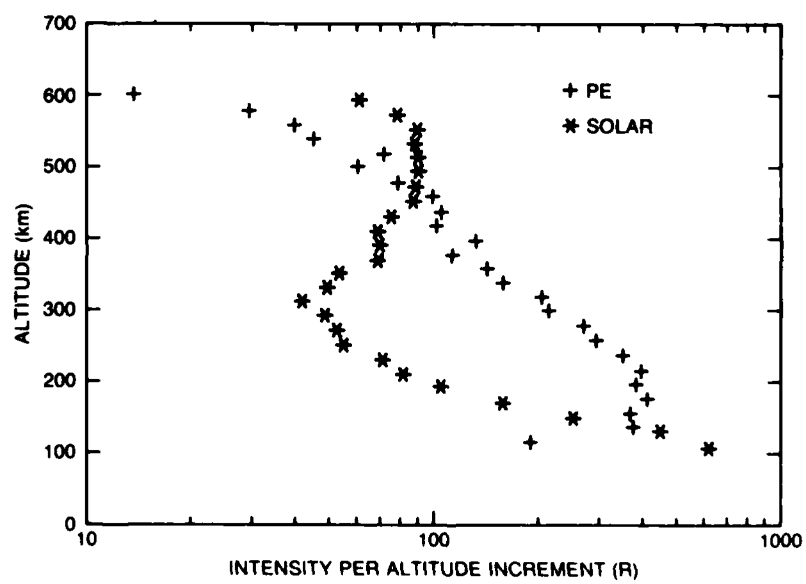

Fig. 1 — Altitude plots of the vertical intensity increments reaching the top of the atmosphere from each of the altitude intervals in the OI 1304 Å multiple scattering model. PE and solar indicate the contributions from photoelectron excitation and solar resonant scattering. The sum of all points gives the total intensity in Rayleighs (R). The model of Meier and Lee (1982) was used. The solar zenith angle was 56°.

We envision several scenarios resulting from a (persisting) depletion of atomic oxygen. In the case of vertical viewing in the nadir (previously discussed), if all of the oxygen in a 50 km diameter column down to 300 km were removed, more than 60% of the intensity would remain because the column below would still be strongly illuminated from all directions other than above; if all of the atoms in a column below 300 km were removed, those above would still emit about 35% of the surrounding intensity. Thus partial depletion of a column along the line of sight would not produce the contrast observed by DE-1. In the more likely situation of oblique viewing of a depleted column, foreground and background emission would render the hole nearly unobservable. Alternatively, if an incoming comet blew out nearly all of the atoms along its path, and the path were always aligned with an instrumental field of view, then the depletion would be holelike with a large contrast. However these two conditions are quite unlikely. Thus there is little possibility that the events observed by DE-1 were actual holes in the oxygen atmosphere.

If, on the other hand, the holes consisted of persistent clouds of absorbing material at, say, 300 km, it is unlikely that the 1304 Å intensity would be reduced by the 80% to 95% observed by DE-1, again because about 35% of the emission would originate in the foreground above the cloud. For a cloud at 200 km, the contrast would be even less. Thus it is quite unlikely that absorbing material at 300 km (or below) could account for the holes observed by DE-1.

If an entire 50-km-wide atmospheric column were filled with absorptive material left behind in the trail of a comet, the required intensity reduction could take place. Again, unless the column were always aligned with a pixel line of sight, there would be too much emitting oxygen in the foreground to allow a reduction in brightness by as much as 80% to 95%.

If an embedded absorbing cloud were much greater than 2000 km^2 in horizontal extent, it would actually be possible to achieve the reduction in brightness observed by DE-1. This scenario was simulated by use of the Monte Carlo model of Meier and Lee by positioning at various altitudes between 200 and 300 km, a 30-km-wide absorbing layer of optical depth 2 and infinite horizontal extent. The emission rate leaving the top of the atmosphere was indeed reduced by an order of magnitude, relative to the case with no absorbing layer. However, such large absorbing clouds are inconsistent with the DE-1 observations.

Thus we conclude that it is unlikely that either reduction in emitters or the presence of absorbers within the 1304 Å radiation field could explain the DE-1 hole phenomena. A possible exception is the hypothesis that the DE-1 observations are only of holes aligned with the instrument field of view. In this case, only a small fraction of the events would be observed, so that the implied rate of occurrence of all events would be impossibly high.

OGO-4 OBSERVATION

The OGO-4 spacecraft was launched on 28 July 1967, reaching a polar (86° inclination) orbit, with initial apogee and perigee of 908 and 412 km, respectively. The spacecraft was 3-axis stabilized. The local time of the orbit was near 15^h at launch and had precessed to near 11^h by the end of October 1967. The NRL instrument consisted of four photometers employing unity gain ion chamber detectors. A Lyman alpha photometer pointed near the zenith while a second Lyman alpha photometer and two FUV photometers covering the bands 1230 to 1350 Å pointed to the nadir. The latter two photometers could not be operated simultaneously. In the dayglow, the 1230 to 1350 Å photometer was sensitive mainly to OI 1304 Å, and the 1350 to 1550 Å instrument observed N_2 LBH bands. A summary of the instruments is given by Chubb and Hicks (1970). The spectral response of the different channels is given in Figs. 1 and 2 of Hicks and Chubb (1970). The OGO-4 band passes do not have the long-wavelength response of DE-1 because of the sharp photoionization thresholds of

the ion chamber gases. The time constant of the electrometers was shorter than 1 s. The instruments were sampled every 0.25 s in the OGO-4 main commutator mode and as much as 8 times faster in flexible format modes. The field-of-view half-angle of the FUV photometers was 23°. These fields of view provide a spatial resolution comparable to that of the DE-1 instrument, considering their relative altitudes. For example, at apogee (3.6 Earth radii), the 0.29° angular diameter of DE-1 corresponds to a horizontal distance of about 120 km at 300 km altitude. When OGO-4 was at 440 km, the same spatial resolution as DE-1 was achieved for viewing an object at 300 km.

OGO-4 operated from July 1967 through January 1969. Unfortunately, because of a spacecraft problem in which the nadir viewing instruments were pointed at the sun near the end of August 1967, the 1304 Å photometer began to lose sensitivity and by the beginning of October 1967 was no longer operating. OI 1304 Å data from this instrument were reported by Meier and Prinz (1971). The LBH photometer operated successfully throughout the mission; results from this instrument were published by Prinz and Meier (1971). The high quality of the data can be seen from the samples presented in the preceding references. Four stages of linear gain change current amplification, each an order of magnitude less sensitive than the previous stage, were available for both photometers. Most of the dayglow data were obtained on the second and third ranges. The signal-to-noise ratio was excellent for both FUV instruments, the noise level ranging from about 5% at large solar zenith angles in the most compressed strip charts to better than 1% at smaller solar zenith angles. Thus we feel that a depletion in the airglow of 5% would be observable by OGO-4, and we set this as the limit of sensitivity in the interpretation of the OGO-4 data. A depletion of 80% to 95%, as reported from DE-1, would be easily observable, since the electrometer would rapidly switch to a more sensitive amplification range.

All data in the August-October 1967 period (240 orbits of OI 1304 Å data and 477 orbits of LBH data), as well as all data in April 1968 (286 orbits of LBH data) were scrutinized for the appearance of holes in the form of negative excursions of >5% in the signal. Spurious events were observed in the OGO-4 data but were rejected as evidence for holes, primarily on the basis that they had repeatable characteristics that could be associated with spacecraft operations or geophysical locations (e.g., the auroral zone). As a check for seasonal or other sampling considerations, an additional 100 orbits per month through September 1968 were examined for holes in the LBH data. In summary, 240 orbits of OI 1304 Å data and 1763 orbits of N_2 LBH data were searched for holes. None was found.

DISCUSSION AND CONCLUSIONS

In this report, we address two interpretations of the holes. The first is that the holes are situated in the atmosphere, lasting on the order of minutes. The second is that they are not in the atmosphere at all, but rather are moving clouds of absorbing material that pass between the spacecraft and the airglow layers. With respect to the first hypothesis, we have shown theoretically that persistent (minutes long) holes in the 1304 Å airglow observed by Frank et al. (1986a) are not likely to be caused by either absorptive material embedded in the atmosphere or to depletion of emitters in an atmospheric column. With respect to both hypotheses in a search for intensity depletion events in OGO-4 data, no holes were found. We now examine the ramifications of these two explanations in relation to the LBH observations from OGO-4.

The 1304 Å data are difficult to interpret because the observations were made from within the emitting atmosphere. A two-dimensional radiative transport model is required to calculate contrasts. For the reasons given earlier, it is expected that the contrast would be low unless the absorbing material passed close to OGO-4. On the other hand, the LBH airglow is produced below 300 km, so all OGO-4 observations were made from outside the emitting region. Therefore we can predict the

rate occurrence of holes expected from the interpretation that the DE-1 events consist of persistent absorptive material embedded in the atmosphere. We make the simplifying assumption that the opacity at LBH wavelengths is large.

During the day in the fall of 1967, the mean altitude of OGO-4 was about 450 km. If a DE-1 hole event were interpreted as a 2000 km^2 area cloud of completely absorbing gas in the atmosphere, and if it were located at 200 km, 5.6% of the OGO-4 footprint (35,400 km^2) would be obscured, close to the limit of the OGO-4 detectability. A cloud located at a lower altitude would not be observable by OGO-4. Such a hole event would appear as a depression in the airglow data lasting 28 s on the average (the time required for the OGO-4 line of sight to move one field of view diameter at 200 km). We can now estimate the number of holes that should have been seen by OGO-4 if persistent clouds were located at 200 km. Frank et al. (1986a) report a mean occurrence frequency of $f = 10$ events per min on the day side of Earth. Using a mean lifetime, τ, of 1 min (defined here as the time interval between the points where the intensity dropped to 50%; Frank et al., 1986a, Fig. 4), in the steady state there are $N = f\tau = 10$ holes present in the airglow from the sunlit hemisphere. Thus the number of holes expected to be observed in the OGO-4 data is $N_{OGO} = N \times A_{OGO}/A_E$ where A_{OGO} is the total area observed by OGO-4 for the records examined and A_E is the area of sunlit hemisphere. The area observed by OGO-4 can be written as $A_{OGO} = A_{FOV} \times \Delta t_{OGO}/28$ s, where A_{FOV} is the projected area of a photometer field of view, and Δt_{OGO} is the total observing time interval of the data that were searched for holes (1763 orbits $\times$ 2400 s/orbit). At an altitude of 200 km, $A_{FOV} = 35{,}400$ km^2 and $A_E = 2.71 \times 10^8$ km^2. With these values, $N_{OGO} = 4.66 \times 10^{-5} s^{-1} \times \Delta t_{OGO}$. The number of holes expected in the LBH channel is 198.

If the clouds were located at 300 km, rather than 200 km, the contrast due to obscuration would increase to 16%, but the area observed by an OGO-4 field of view decreases to 12,900 km^2. The number of holes expected then drops to 71 for the LBH photometer. This number is still sufficiently large that the negative results exclude the possibility of clouds persisting for 1 min at altitudes between 200 and about 300 km in the atmosphere. These arguments are based on the geometric effect of an opaque cloud of absorbing material persisting in the atmosphere. Of course, if the contrast is always low in LBH bands, a hole would not be observed, no matter what the geometry; however, Frank et al. (1986a) did report the occurrence of holes in their LBH data.

In summary, we conclude from theoretical arguments that it is unlikely that the holes are persistent (minutes) features in the 1304 Å airglow, and that the OGO-4 observations support that conclusion unless the absorbing clouds are transparent between 1350 and 1550 Å.

A picture of the hole phenomenon alternative to the published explanation has been suggested by Frank (private communication, 1986; Frank et al., 1986c) in which the *piston* of cometary gas passes through a DE-1 field-of-view pixel between the breakup altitude near 2000 km and the top of the OI 1304 Å emitting region (about 600 to 800 km). This explanation has also been alluded to by Frank et al. (1986d). In this case the airglow is intercepted before reaching the spacecraft by absorbtive material above the atmosphere. This hypothesis can be tested with OGO-4 data if we consider the region of observability as a right circular cone of 23° half angle, extending downward from 450 to 200 km. The area of the base averaged over the length of the conic section is about $A = 12{,}000$ km^2 and the average contrast is 2000/12,000 or 17%. A hole would appear as a depression in the airglow data lasting an average time ($t = d/v$) that it takes for an object of velocity v to cross a distance ($d = 2\sqrt{A/\pi}$); $v = 20$ km s^{-1}, and $t = 6$ s. Of course events closer to OGO-4 would last a shorter time but would have greater contrast. We can now estimate the average number of events that should have been seen in the OGO-4 data. This number is given by the product of the average flux on the

sunlit hemisphere, the average area to be crossed, and the observing time. These quantities are 6×10^{-10} km^{-2} s^{-1}, 12,000 km^2, and 1763 orbits $\times$ 2400 s/orbit = 4.2×10^6s. Thus some 30 events would have been expected, while none was seen.

However, our experience with the OGO-4 data is that an event as short as 6 s would be difficult to observe unless the contrast were 20% or greater. Still, we might expect to have seen some portion of events that have large contrasts or longer time intervals. Unfortunately, it is difficult to quantify this comment without more details of the DE-1 LBH data.

A possible interpretation of the lack of holes in the OGO-4 data (irrespective of which Frank et al. explanation of the hole phenomena is used) is the combined set of conditions that the absorber is gaseous H_2O, the size of a cloud always just fills a DE-1 pixel, and the cloud optical depth is always less than about 3 at 1304 Å. Under these conditions, the reduced absorption cross section in the 1350 to 1550 Å LBH band would render the contrast below levels detectable by OGO-4. However evidence from the DE-1 data is that all of these conditions are not met since Frank et al. (1986a) have observed holes in the LBH airglow. Unfortunately little information on hole events in LBH data is available from DE-1.

We conclude from theoretical arguments and from OGO-4 observations that the holes in the FUV airglow seen in DE-1 data are not due to persistent (~ minutes) phenomena in the atmosphere. While observations from OGO-4 cannot rule out an alternative explanation that absorbing material passes between an observer's field of view and the airglow, we would expect that at least some events would have been seen in the OGO-4 data. However, even in this alternative explanation, eventually the clouds must pass through airglow layers in the atmosphere. Any model that proposes an interaction between the clouds and the airglow-producing thermosphere must be constrained by both the 1304 Å theoretical considerations and the OGO-4 observations.

ACKNOWLEDGMENTS

P. Mange was the principal investigator on OGO-4. Valuable discussions of this work were held with D. E. Anderson, W. Hanson, R. R. Conway, J. L. Lean, and R. P. McCoy.

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